

## Stephan's Quintet: A Multi-galaxy Collision

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**Abstract** Stephan's Quintet (SQ), discovered more than 100 years ago, is the most famous and well studied compact galaxy group. It has been observed in almost all wavebands, with the most advanced instruments including Spitzer, GALEX, HST, Chandra, VLA, and various large mm/submm telescopes/arrays such as the IRAM 30m and BIMA. The rich multi-band data reveal one of the most fascinating pictures in the universe, depicting a very complex web of interactions between member galaxies and various constituents of the intragroup medium (IGM), which in turn trigger some spectacular activities such as a 40 kpc large scale shock and a strong IGM starburst. In this talk I will give a review on these observations.

**Key words:** galaxies: interactions: intergalactic medium: ISM: starburst: active

### 1 INTRODUCTION

As an interacting galaxy system, Stephan's Quintet (hereafter SQ) is not as famous as Arp 220 or M82. Taken as a 'popularity index', the number of references listed by NED (until Dec. 18th, 2005) under 'Stephan's Quintet' is only 104, far less than that under 'M82' (1355) and 'Arp 220' (563). However, its fame as a very special case of multi-galaxy collision has been rising steadily recently, thanks mostly to the ever increasing number of observational windows opened one after another in this space astronomy era. SQ has been observed in almost all wavebands, and it keeps revealing surprises when being looked at by new instruments.

Different from binary galaxies and mergers which have been thoroughly discussed elsewhere in this conference, SQ belongs to a different class of interacting systems of galaxies: the compact groups (Hickson hic82) that are characterized by aggregates of 4 – 8 galaxies in implied space densities as high as those in cluster cores. SQ is unique among its peers because a seemingly very rare event is occurring to it: a high velocity ( $\sim 1000$  km sec $^{-1}$ ) intruder is colliding into a debris field in the intragroup medium (IGM), the latter being a product of previous interactions among other member galaxies of the group. The complex web of galaxy-galaxy and galaxy-IGM interactions have triggered all kinds of interaction related phenomena, including a large scale shock ( $\sim 40$  kpc), an IGM starburst, long tidal tails ( $> 100$  kpc) with tidal dwarf candidates, and a highly obscured type II AGN.

In this talk I'll review the rich literature on the multi-frequency observations of SQ and the constraints imposed on its interaction history and on its current star formation rate. I'll also highlight its role as a laboratory to study rare phenomena such as large scale shocks and

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Figure 1 SQ members and two tidal tails. The isodensity image of a photographic plate is taken from Arp (1973a).

high velocity collision induced starbursts. Inferences from these studies to the understanding of local ULIRGs and high  $z$  galaxies will be briefly touched.

## 2 EARLY LITERATURE AND MEMBERSHIP OF SQ

SQ (Fig.1) was discovered as an aggregation of nebulae by Stephan in late 19th century (Stephan 1877), much earlier than anyone knew galaxies outside the Milky Way exist. It raised strong interest in early years of modern astronomy because of its wide range of redshifts (Ambartsumian 1958; Limber & Mathews 1960; Burbidge & Burbidge 1971). In particular, Arp(1973a,1976) argued that NGC 7320, with a redshift about  $5000 \text{ km sec}^{-1}$  less than the rest of the group (Burbidge & Burbidge 1971), is physically associated with other SQ galaxies and is a prime case for the existence of non-Doppler redshift. The counter arguments against this claim include (Allen & Sullivan 1980; Moles et al. 1997): (1) No evidence for interaction with other SQ galaxies was found in the HI or in the  $\text{H}\alpha$  emission associated with NGC 7320. (2) Results from redshift independent estimators yielded distances consistent with the redshifts. (3) Apparently NGC 7320 is a member of a foreground loose galaxy group which includes the large galaxy NGC 7331 at redshift  $\sim 800 \text{ km sec}^{-1}$ . I shall assume that NGC 7320 is a foreground galaxy and omit it hereafter. Arp (1973b) suggested that NGC 7320c, a galaxy about  $4'$  to the east of NGC 7319 and linked to the group by optical tidal tails, should be included into SQ. Therefore, dropping NGC 7320 and at same time picking up NGC 7320c, SQ still consists of five galaxies as implied by the name.

## 3 INTERACTION HISTORY

The early deep optical images (Arp & Kormendy 1972; Arp 1973a; Arp & Lorre 1976) show clearly two concentrating parallel tidal tails, both starting from NGC 7319 and extending to NGC 7320c, with the more diffuse one passing through the low redshift galaxy NGC 7320.

### 3 INTERACTION HISTORY

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However, contemplations on the interaction history of SQ started only after two discoveries in the radio band, both made with the Westerbork Synthesis Telescope. The first is a huge ( $\sim 40$  kpc) radio continuum ridge found in the IGM between NGC 7319 and NGC 7318b (Allen & Hartsuiker 1972). Among other possible interpretations, Allen & Hartsuiker suggested this may be a large scale shock triggered by an on-going collision between NGC 7318b and the rest of the group. The second (Allen & Sullivan 1980; Shostak et al. 1984) is the revelation that nearly all HI gas associated with SQ, amounting to  $\sim 10^{10} M_{\odot}$ , is in the IGM outside galaxy disks. It is suggested that this is stripped gas from late type galaxy disks due to an earlier interaction (a few  $10^8$  yr ago) either between NGC 7319 and NGC 7318a (Allen & Sullivan 1980), or between NGC 7319 and NGC 7320c (Shostak et al. 1984).

Mole et al. (1997, hereafter M97) put up a comprehensive picture for the interaction history of SQ based on a 'two-intruders' scenario (see also Sulentic et al. 2001, hereafter S01): an old intruder (NGC 7320c) stripped most of the gas from group members, and a new intruder (NGC 7318b) is currently colliding with this gas and triggering the large scale shock. The 'old intruder' passed the core of SQ twice, one in  $\sim 5 - 7 10^8$  yr ago and pulled out the 'old tail', another about  $2 10^8$  yr ago and triggered the 'young tail' (the narrower one). Recently, Xu et al. (2005, hereafter X05) proposed a 'three-intruders' scenario based on new observations. They agreed with M97 on the origins of the old tail and of the shock. But, different from M97, they argued that it is unlikely that the 'young tail' is also triggered by NGC 7320c. This is because the recently measured redshift of NGC 7320c ( $6583 \text{ km sec}^{-1}$ , S01) is almost identical to that of NGC 7319, indicating a slow passage (S01) rather than a fast passage ( $\sim 700 \text{ km sec}^{-1}$ , M97). In order for NGC 7320c to move to its current position, the NGC 7319/7320c encounter must have occurred  $\gtrsim 5 10^8$  yr ago. This is close to the age of the old tail, but older than that of the young tail. They suggested that the young tail is triggered by a close encounter between the elliptical galaxy NGC 7318a and NGC 7319. The projected distance between NGC 7318a/7319 is only  $\sim 1/3$  of that between NGC 7320c/7319. Therefore the time argument is in favor of the new scenario. Also the morphology of the 'young tail' revealed by the new UV observations, relative to NGC 7319 and NGC 7318a, looks very similar to the 'counter tidal tail' found in dynamic simulations of equal mass galaxy-galaxy interactions (see, e.g., Fig.2 of Toomre & Toomre 1972,  $t=2 10^8$  yr). According to the K-band luminosities, NGC 7318a and NGC 7319 have nearly identical stellar mass.

Moles et al. (1997; 1998) concluded that the disk of NGC 7318b is still intact because the time since it starts to interact with the group is too short ( $\sim 10^7$  yr) for any tidal effect. However, Xu et al. (2003; 2005) speculated that the galaxy might have had a head-on collision with NGC 7318a  $\sim 10^8$  yr ago, which means NGC 7318a must be  $\sim 100$  kpc further away than NGC 7318b given the velocity difference. This will help to explain the long outer arms (looking like tidal tails), the peculiar HI gas distribution (all outside the optical disk) and the huge UV disk ( $\sim 80$  kpc) of the NGC 7318b. Also, in this scenario, the comma-like filaments in the region north of NGC7318 (see, e.g. Fig.1c of Mendes de Oliveira et al. 2001) can be interpreted in an analogy to the spoke-like filaments in the Cartwheel Galaxy, a prototype ring galaxy produced in a head-on galaxy-galaxy collision (Higdon 1995).

The only sign for any interaction between NGC 7317 with other members of SQ is a common halo linking it to the binary NGC 7318, found in the deep X-ray and optical R-band images (Trinchieri et al. 2005).

## 4 THE LARGE SCALE SHOCK

Since the discovery of Allen & Hartsuiker (1980), the large scale radio ridge has been confirmed by later VLA observations (van der Hulst & Rots 1981; Williams et al. 2002, hereafter W02; Xu et al. 2003). The high resolution X-ray maps (Pietsch et al. 1997; S01; Trinchieri et al. 2003, 2005) and optical narrow-band H $\alpha$ /[NII] maps (Vilchez & Iglesias-Páramo 1998; Ohyama et al. 1998; Xu et al. 1999; Plana et al. 1999; S01) show a similar structure, in both the hot gas and the ionized gas. The optical spectroscopy of Xu et al. (2003) at several positions along the ridge show spectra consistent with shock excitation. This shock is truly unique to SQ. Its size is second only to that of the radio relics caused by cluster mergers (Enßlin & Brüggen 2002). In the shock, the intruder/IGM collision could have deposited as much as  $10^{56}$  erg energy, equivalent to the kinematic energy of  $\sim 100,000$  supernovae. Using the formula of Dopita & Sutherland (1996), Xu et al. (2003) derived a total energy flux in the form of  $L_T = 2.1 \times 10^{42}$  erg sec $^{-1}$ . Apparently, most of this flux comes out in the FIR band. Based on ISO observations, the total dust luminosity of the shock front is  $L_{\text{dust}} = 1.9 \times 10^{42}$  erg s $^{-1}$ . This is about an order of magnitude higher than the X-ray luminosity (Trinchieri et al. 2003), indicating that the hot gas is predominantly cooled by collisions with dust grains. Trinchieri et al. (2003) estimated the shock velocity to be 460 km sec $^{-1}$ , and the density of post-shock gas  $n_H = 0.027$  cm $^{-3}$ . The corresponding sputtering time scale for  $a = 0.1\mu\text{m}$  grains is  $3.7 \times 10^6$  yr, compared to the cooling time scale of  $2.1 \times 10^6$  yr. Hence the grains can indeed survive the shock long enough to be the major coolant. The energy density of relativistic particles plus the magnetic fields, derived from the minimum energy assumption, is  $U_{\text{min}} \sim 1.0 \times 10^{-11}$  erg cm $^{-3}$  (Xu et al. 2003). This is significantly lower than the total energy density implied by the total energy flux, so the magnetic field may be dynamically insignificant for the shock. Recently, using Spitzer, Appleton et al. (2006) discovered strong mid-IR emission lines of molecular hydrogen (and little else!) at position of one of the radio emission peaks along the shock. The derived H $_2$  luminosity is much higher than L $_X$  and only a factor of  $\sim 3$  less than L $_{\text{dust}}$ . This gives support to the idea (Rieke et al. 1985) that the strong MIR H $_2$  lines often detected in luminous IR galaxies are primarily excited by shock waves.

## 5 STAR FORMATION

The star formation activity in SQ is apparently very much influenced by interactions. The most spectacular star formation region in SQ is the IGM starburst SQ-A, which is associated with a bright MIR ( $15\mu\text{m}$ ) source (Xu et al. 1999) just beyond the northern tip of the shock front. The two velocity components of the starburst have same redshifts as those of the neutral gas, indicating that the starburst is occurring in the pre-shock gas. The estimated star formation rate (SFR) is  $1.45 \text{ M}_\odot/\text{yr}$ , and the age is  $\sim 10^7$  yr. Xu et al. (2003) advocated a scenario in which the starburst is triggered due to squeezing of pre-existing giant-molecular clouds (GMCs) by post-shock HI gas, as depicted in the model of Jog & Solomon (1992). The 'young tail' is also active in star formation. Hunsberger et al. (1996) found 13 'tidal dwarf galaxy candidates' along this tail. A bright star formation region (SQ-B) is detected in both H $\alpha$  (Arp 1973a) and MIR (Xu et al. 1999). Several discrete star formation regions near the western tip of the tail are found in both H $\alpha$  (S01; Mendes de Oliveira et al. 2004) and FUV (X05). The H $\alpha$  images (Arp 1973a; Vilchez & Iglesias-Páramo 1998 1998; Plana et al. 1999; S01) reveal numerous

huge HII regions along several arms of NGC 7318b. Hunsberger et al. (1996), Iglesias-Páramo & Vilchez (2001), and Mendes de Oliveira et al. (2001) classified them as tidal dwarf galaxy candidates, though S01 argued that the crossing time of NGC 7318b ( $\sim 10^7$  yr) is too short for any tidal effects. Investigations based on optical colors (Schombert et al. 1990; Gallagher et al. 2001) and UV colors (X05) indicate several distinct epochs of star formation that appear to trace the history of dynamic interactions in SQ. Using the  $H_{\alpha}$  luminosity without correction for internal extinction, the results of Iglesias-Páramo & Vilchez (2001) give a rather low net SFR of  $\sim 1 M_{\odot}/\text{yr}$  for the whole group. The extinction corrected FUV (GALEX) luminosities, with internal extinction constrained by the ISO MIR flux and the HI surface density, yield a net SFR of  $6.7 \pm 0.6 M_{\odot}/\text{yr}$  (X05). The SFR of the two Sbc galaxies, NGC 7318b and 7319, is consistent with that of normal Sbc galaxies such as the Milky Way, confirming the general conclusion that late type galaxies in compact groups have their SFR indistinguishable from that of their field counterparts (Sulentic & De Mello Rabaca 1994; Moles et al. 1994; Iglesias-Páramo & Vilchez 2001). This is in strong contrast with galaxy pairs where significant enhancement of star formation is very common.

## 6 INTRA-GROUP MEDIUM (IGM)

**HI gas:** First noticed by Allen & Sullivan (1980), and confirmed by later observations (Shostak et al. 1984; W02), all of the HI in SQ is in the IGM outside galaxy disks. W02 found the gas is located in five features: (1) Arc-S ( $6641 \text{ km sec}^{-1}$ ,  $2.5 \cdot 10^9 M_{\odot}$ ) associated with the old optical tail, (2) Arc-N ( $6604 \text{ km sec}^{-1}$ ,  $4.0 \cdot 10^9 M_{\odot}$ ) associated with the young tail, (3) NW-LV ( $6012 \text{ km sec}^{-1}$ ,  $2.2 \cdot 10^9 M_{\odot}$ ) and (4) NW-HV ( $6647 \text{ km sec}^{-1}$ ,  $0.9 \cdot 10^9 M_{\odot}$ ) both centered at the position of the IGM starburst SQ-A, and (5) SW ( $5699 \text{ km sec}^{-1}$ ,  $1.5 \cdot 10^9 M_{\odot}$ ) in the south of NGC 7318b. These authors emphasized the uncertain origin of these HI features. On the basis that SW and NW-LV features are spatially and kinematically separated with each other, W02 argued against the scenario that both features belong to NGC 7318b, each on the opposite side of a rotation disk (M97). However, a comparison between the FUV image (X05) and a new, higher resolution and higher sensitivity VLA B-array HI map (Yun et al. 2006) shows that SW and NW-LV indeed coincide very well with FUV arms belonging to a very large FUV disk ( $\sim 80 \text{ kpc}$ ) centered on the nucleus of NGC 7318b, lending support to their associations with NGC 7318b.

**Molecular Gas:** The early millimeter CO observations (Yun et al. 1997; Verdes-Montenegro et al. 1998; Leon et al. 1998) detected molecular gas only in the disk of NGC 7319, amounting to  $4.8 \cdot 10^9 M_{\odot}$  (Smith & Struck 2001). This is normal for its size and luminosity (Lisenfeld et al. 2002). The molecular gas associated with the IGM starburst SQ-A is first detected by Gao & Xu (2000) using BIMA, later confirmed by single dish observations of Smith & Struck (2001) and Lisenfeld et al. (2002). The CO emission is in two separate velocity systems centered at  $6000 \text{ km sec}^{-1}$  and  $6600 \text{ km sec}^{-1}$ , respectively, in excellent agreement with the redshifts of the two HI features found in the same region (NW-HV and NW-LV in W02). It is interesting to note that, according to Lisenfeld et al. (2002), there is more molecular gas ( $3.1 \cdot 10^9 M_{\odot}$ ) in SQ-A than in HI gas ( $2.5 \cdot 10^9 M_{\odot}$ ). Braine et al. (2001) detected CO in SQ-B, a ‘tidal dwarf’ (TDF) candidate bright in MIR (Xu et al. 1999),  $H_{\alpha}$  (Arp 1973a) and UV (X05). The follow-up observations of Lisenfeld et al. (2002; 2004) found  $7 \cdot 10^8 M_{\odot}$  molecular gas. The

ratio  $M_{H_2}/M_{HI} = 0.5$  is consistent with the average of TDFs. From the close correspondence between the CO, HI, H $\alpha$  and MIR emission, Lisenfeld et al. (2004) argued that the HI feature Arc-N (W02) is linked to the young optical tail, therefore is very likely to be originated from NGC 7319. A survey for CO emission associated with other TDF candidates (Mendes de Oliveira et al. 2001) yielded no detection. CO emission associated with NGC 7318b nucleus and with several other regions in the disk was reported in Gao & Xu (2000), Smith & Struck (2001), Pettpas & Taylor (2005). Metallicity has been determined for SQ-A and SQ-B, in both cases it is slightly higher than solar (Xu et al. 2003; Lisenfeld et al. 2004), suggesting that the IGM gas is originated in the inner part of a galaxy disk (or disks).

**Hot Gas (X-ray):** SQ has been observed by almost every X-ray satellite, including Einstein (Bahcall et al. 1984), Rosat (Sulentic et al. 1995; S01; Pietsch et al. 1997), ASCA (Awaki et al. 1997), Chandra (Trinchieri et al. 2003) and XMM (Trinchieri et al. 2005). Trinchieri et al. (2005) divide the X-ray emission in SQ into 4 major features: (1) the shock, (2) NGC 7319 (Sy2), (3) HALO, (4) TAIL. TAIL is associated with hot diffuse IGM that cannot be ascribed to the shock. It has a size of 130 — 150 kpc and is in a region coinciding with the eastern end of the old optical tail, indicating a link to the early tidal interactions. HALO includes the diffuse emission in a region surrounding the shock, excluding the shock itself and emissions possibly related to individual galaxies. These two diffuse features take  $\sim 50\%$  of the total soft X-ray (0.5 — 2.0 keV) luminosity of SQ.

**Dust:** SQ was detected, but barely resolved, by IRAS (Allam et al. 1996; Yun et al. 1997). The higher resolution and more sensitive ISO observations (Xu et al. 1999, 2003; S01) found most of the MIR (11.3 and 15 $\mu m$ ) and FIR (60 and 100 $\mu m$ ) emission in the disks of NGC 7319 and of the foreground galaxy NGC 7320. Two IGM starbursts SQ-A and SQ-B, both including several previously detected HII regions, stand out in the 15 $\mu m$  image due to their strong MIR emission (Xu et al. 1999). There is evidence for dust emission in the shock front, and the dust cooling is likely to be the dominant cooling mechanism for the shock (Xu et al. 2003; Trinchieri et al. 2005). The ISOPHOT maps at 60 $\mu m$  and 100 $\mu m$  indicate that there might be diffuse dust emission in the IGM, but the signal is marginal. This has been followed up by Spitzer observations at 70 $\mu m$  and 160 $\mu m$  (Xu et al. 2006). With much improved sensitivity and angular resolution, the Spitzer 160 $\mu m$  indeed detected significant diffuse dust emission outside individual galaxies, amounting as much as more than 50% of the total  $L_{160\mu m}$  of SQ. The origin of this emission is still unclear. There are two competing possibilities: (1) emission of collisionally heated grains in the hot IGM; and (2) emission of radiative heated grains in the cold neutral IGM. The better correspondence between the morphology of the 160 $\mu m$  map and that of the X-ray map, compared to that between 160 $\mu m$  and HI, favors the possibility (1).

## 7 SY2 NUCLEUS OF NGC 7319

The AGN was first recognized by van der Hulst and Rots (1981) in the VLA observations of SQ at 20cm continuum. They detected a bright compact source with a jet-like extension, and suggested this might be related to those found in Seyfert galaxies. Huchra et al. (1982) obtained the optical spectrum which shows clearly Sy2-type emission-line features. Based on the stellar velocity dispersion, Woo & Urray (2002) estimated the black hole mass:  $M_{BH} = 10^{7.38} M_{\odot}$ . Aoki et al. (1999) made VLA A-array radio continuum observations, complimented with an

archival HST optical image. They found a chain of 3 radio sources, interpreted as the nucleus and its two jets on opposite sides. Optical features are found in the HST image closely related to the radio jets, interpreted as gas compressed and excited by bow shocks driven into the ambient medium by the jets. This is different from the so-called extended emission line regions (EELR) which are supposedly excited by the AGN radiation (Aoki et al. 1994). Even higher resolution ( $0.16''$ ) radio continuum observations at 1658 MHz, using MERLIN, were reported by Xanthorouplios et al. (2004). They compared the data with an HST/ACS U-band (F330W) image, and found extended UV emission around the nucleus and the northern jet. They argued that this indicates star formation triggered by the jet/ISM interaction. By assuming the diffuse radio emission outside the compact sources is due to the star formation, they estimated that the SFR in the circum-nuclear region is  $8.4 M_{\odot}$ . However, all of the optical spectra of emission line regions in the circum-nuclear region show Seyfert or LINER line ratios and none is HII region-like (Aoki et al. 1994), indicating that most of the radio and UV radiation is related to the AGN and/or the shocks. Comparing the UV and MIR observations, X05 found the AGN and the surrounding region is highly obscured, with an FUV extinction of  $A_{\text{FUV}} = 5.4$  mag, consistent with the Sy2 classification.

## 8 SUMMARY REMARKS

The fascination of SQ is due to its rich history full of interactions, which we are just starting to unveil. Although the multi-wavelength observations in the literature have provided clues on how the different events may be related to each other, a clear-cut picture is yet to emerge. Many interpretations are based on dynamic simulations for binary galaxies, which may not be appropriate for multi-galaxy collisions such as SQ. Dedicated simulations for SQ are certainly desired. Such simulations will provide insights on how compact groups such as SQ survive merging, at the same time turn late-type galaxies into early types without significantly increasing the SFR. Investigations on the difference between multi-galaxy collisions and two-galaxy collisions will shed light on how galaxy interactions may have contributed to the evolution of galaxies and galactic structures.

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